

# THE ENERGY OUTPUT OF THE UNIVERSE

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**ABSTRACT** The total energy emitted by the growth of massive black holes is large and can be 10-50 per cent of that emitted by stars in the universe. I show how the X-ray Background provides a good measure of this energy and also why most accretion power is absorbed and re-emitted in the far infrared band. A model for the obscured growth of massive black holes is presented which accounts for both the high absorption and the observed black hole to galaxy spheroid mass correlation. Future missions should detect the obscured X-ray sources associated with the growth of massive black holes.

**KEYWORDS:**

## 1. INTRODUCTION

The X-ray Background (XRB) is the integrated emission from all X-ray sources. Its hard spectrum has proved difficult to explain since, in the 2–10 keV band, it is flat with a power-law of energy index 0.4. This is flatter than the spectrum of any known common population of objects. For the last decade the most popular explanation has been that the XRB intensity is dominated by many absorbed sources (Setti & Woltjer 1989), with ranges of absorbing column density and redshift causing the observed spectrum to be a power-law. The absorption model has been extensively studied by Madau et al (1994), Matt & Fabian (1994), Comastri et al (1995), Celotti et al (1995), and Wilman & Fabian (1999). The most complete studies include Compton down-scattering in the estimation of the observed spectrum of the Compton-thick sources.

The absorption model is adopted here and is used in a simple way to show that black holes grow by radiatively efficient accretion and to determine a) the local mean density of black holes, b) the fraction of accretion power which has been absorbed, and c) constraints on the fraction of power in the Universe due to accretion (see also Fabian & Iwasawa 1999). After some discussion of how so much obscuring material can surround most sources, and how the nuclei might be fuelled, I then outline a model of obscuration in a forming, isothermal galaxy spheroid (Fabian 1999). The XRB is shown to be a key diagnostic of the accretion power of the Universe.

## 2. ACCRETION AND THE XRB

I assume that the underlying active galactic nuclei (AGN) which power the XRB have a quasar-like spectrum with an energy photon index of one. The spectrum is then constant in a  $\nu F_\nu$  sense (Fig. 1). The action of photoelectric absorption by increasing amounts of material, characterised by a column density  $N_H$ , is (Fig. 2) to cut out the lower energy emission from the observed spectrum up to an (approximate) energy  $E \sim 10N_H^{8/3}$  keV, where  $N_H$  is in units of  $10^{24} \text{ cm}^{-2}$ . As the column density exceeds about  $1.5 \times 10^{24} \text{ cm}^{-2}$  so the absorber becomes Compton thick and Compton (electron) scattering causes the residual spectrum above this cutoff to decrease in intensity. This means that the intensity observed above about 30 keV is close to the intrinsic unattenuated intensity from Compton-thin sources, and is a lower limit for Compton-thick ones. Therefore the intensity of the XRB at 30 keV equals the normalization of the XRB after correction for absorption by Compton-thin sources. This normalization can be increased by a factor of  $f^{-1}$  if only a fraction  $f$  of all the power emerges from sources which are Compton thin.  $f$  is at most 3/4 (Maiolino et al 1998) and could be less than one half.

The absorption-corrected XRB spectrum can then be extended into the ultra-violet band assuming the mean quasar spectral energy distribution of Elvis et al (1994). This shows that about 3 per cent of the power from a typical quasar is emitted in the 2–10 keV band. The total absorption-corrected AGN background can now be converted into an energy density  $\epsilon_{AGN}$  and thence, through the use of  $E = Mc^2$  or rather  $\epsilon(1 + \bar{z}) = \eta\rho c^2$  with an accretion efficiency factor  $\eta$  and a mean redshift  $\bar{z}$  (since photons lose energy in the expansion of the Universe but mass does not), we have the mean density in black holes  $\rho_{bh}$ .

The resulting value of  $\rho_{bh} = 6 \times 10^5 \text{ M}_\odot \text{ Mpc}^{-3}$  is about half the value found by Magorrian et al (1998) from a study of ground-based optical data of the cores of nearby galaxies, and in rough agreement with an HST photometric study made by van der Marel (1999). Similar agreement has been obtained by Salucci et al (1999) from a detailed considerations of source counts etc. This close agreement emphasises that most of the mass in black holes has been accreted by a radiatively efficient (but obscured) process, and not by some inefficient process such as an advective flow. The correction required for absorption is extensive and requires that most, about 85%, of the accretion power has been absorbed.

## 3. AGN, THE FIR BACKGROUND AND THE ENERGY FROM STARS

The absorbed power is assumed to be emitted in the Far Infrared (FIR) bands, and when redshifted it should contribute to the sub-mm background. The total predicted is about  $3 \text{ nW m}^{-2} \text{ sr}^{-1}$  which is several tens percent of total the sub-mm background (Fixsen et al 1997; see also Almaini et al 1999 for estimates of the AGN contribution to the sub-mm background). This suggest that to within a factor of two the total integrated power (ie the total energy released) from accretion onto black holes is about one quarter of that from stars (mostly starlight but including

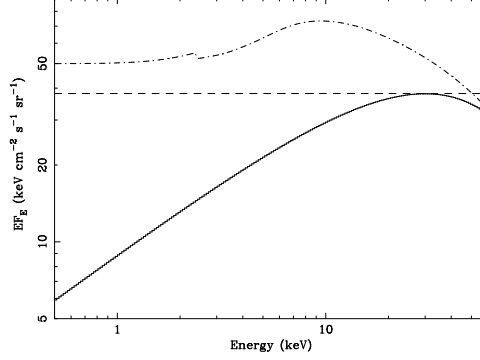


FIGURE 1. XRB spectrum (solid line) with the assumed unabsorbed spectrum of photon index 2 (dotted line). A typical AGN spectrum with reflection, in which the direct emission is a power law of photon index 2 with an exponential cutoff of 300 keV is shown by the dot-dash line, matching around the XRB peak. If unabsorbed quasars contribute 50 per cent of the XRB at 1 keV, then their contribution lies along the bottom of the figure.

supernovae), i.e.

$$E_{AGN}/E_{\star} \sim 0.25.$$

The details of any comparison depend upon the history of the starlight and of the accretion. No estimate of the contribution to the NIR and optical backgrounds, which could lower the above value, has been made here.

A simple check on this is obtained from an argument due to G. Hasinger (see Fabian & Iwasawa 1999). Magorrian et al (1998) find the following relation between the black hole mass  $M_{bh}$  and spheroid mass  $M_{sph}$  of a galaxy:

$$M_{bh} \approx 0.005 M_{sph},$$

so if the total energy radiated

$$E_{AGN} \approx 0.1 M_{bh} c^2$$

then

$$E_{AGN} \approx 0.1 \times 0.005 M_{sph} c^2.$$

But the total energy radiated by stars

$$E_{\star} \approx 0.1 \times 0.005 a^{-1} M_{sph} c^2,$$

where the first term is the fraction of a star which undergoes nuclear fusion and the second is the efficiency (in a  $E = mc^2$  sense) of that fusion.  $a$  is the ratio of the present mass of the spheroid to its original mass (many of the stars have evolved) and for a Salpeter mass function is about 20 per cent. Therefore

$$E_{AGN}/E_{\star} \approx a \approx 0.2.$$

#### 4. UNCERTAINTIES

The above estimate reduces to 0.1 if the scaling relation of van der Marel (1999), which agrees better with the XRB intensity, is used, but can increase towards unity if stellar mass loss is recycled into new stars, so that  $a \sim 1$ . A mass-to-energy efficiency of 0.1 has been used but it can be 0.06 if the black hole is not spinning, or 0.42 if it becomes a maximally spinning, Kerr, black hole.

An even more extreme possibility which defines an upper limit on the efficiency relative to the final (dead) black hole mass is to assume that the black hole was maximally spinning during the accretion phase and then spun down by, say, the Blandford-Znajek (1977) mechanism. The total energy released relative to the final black hole mass allows for an order of magnitude uncertainty in  $\eta$  and thus  $E_{AGN}$ . Of course a high value here, which maximises  $E_{AGN}/E_*$ , overpredicts the XRB intensity unless most of the growing phase of black holes is Compton thick. It is also possible that a significant fraction of the power from an AGN is in the form of a wind and not directly in radiation. As discussed later, growing black holes may be both Compton thick and powering winds. If this is correct, then  $E_{AGN}/E_*$  may be significantly higher than the estimate in the last section.

#### 5. OBSCURATION, METALLICITY AND FUELLING

As outlined above, at least 85 per cent of accretion power is absorbed. Since about ten per cent is in quasars which show very little absorption, this means that most lines of sight out of the remaining objects are highly absorbed. This is difficult for the standard obscuring torus model, which could absorb perhaps one half to two thirds of all sight lines. Even then it is unclear what inflates the torus, which is supposed to be cold and molecular. Dissipation in a system of orbiting clouds should cause it to flatten into a disc, with lowcovering factor.

Energy must be continuously injected into any cold absorbing cloud system to keep it inflated and so sky covering. One plausible solution is that a gas-rich star cluster surrounds the black hole and it is the massive stars (winds and supernovae) which supply the energy (Fabian et al 1998). The surrounding starburst can thereby obscure the active nucleus.

The starburst should enhance the metallicity of the absorbing gas. This makes a given mass of gas more efficient at absorbing X-rays and indeed increases the effect of absorption before Compton down-scattering comes into play. This is important in opening up the parameter space for model-fitting of the XRB spectrum (Wilman & Fabian 1999).

Fuelling of the nucleus is an old problem (see e.g. Shlosman et al 1990). Although there may be lots of gas around the nucleus, angular momentum may prevent it from rapidly accreting to the centre. In this respect, a hot phase in the surrounding medium may be important, with Bondi accretion from this phase being the dominant mechanism (see e.g. Nulsen & Fabian 1999). Angular momentum may be transported outward by turbulence within such a hot phase, so allowing rapid accretion to proceed.

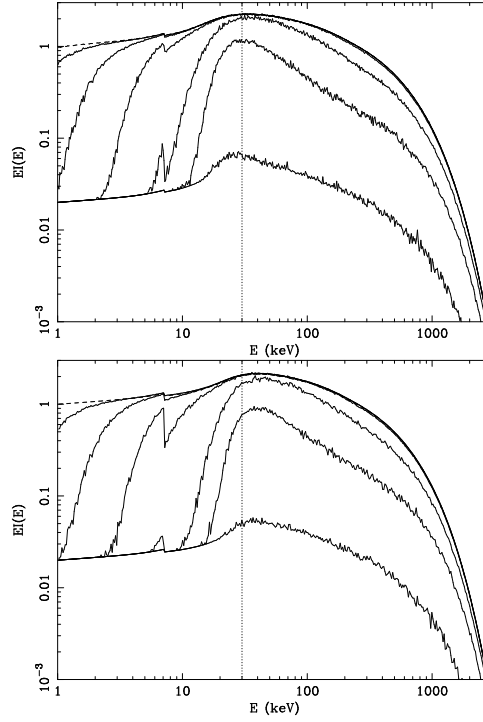


FIGURE 2. Monte-Carlo simulations of of an accretion disc spectrum (a power-law of unit energy index with cold reflection and an exponential cutoff at 360 keV) propagated through a solar abundance spherical cloud of column densities ranging from  $10^{21.25}$  to  $10^{25.25}$   $\text{cm}^{-2}$  in steps of a factor 10. Note that the spectra peak around 30 keV, indicated by the vertical line. The lower panel shows the effect of increasing the iron abundance by 5, which causes the peak to shift to 40–50 keV (from Wilman & Fabian 1999).

## 6. THE MEAN LUMINOSITY OF THE DISTANT AGN DOMINATING THE XRB INTENSITY

Since the mass of the black hole in nearby galaxies appears to be proportional to the spheroid mass, the mass function of black holes must be similar in shape to the spheroid mass function. The mean black hole mass is therefore that appropriate to an  $L^*$  galaxy, or about  $3 \times 10^8 M_\odot$ . The Eddington limit of such a black hole is about  $3 \times 10^{46} \text{ erg s}^{-1}$  and its mass doubling (Salpeter) time is about  $3 \times 10^7 \text{ yr}$ . If the typical mass black hole has therefore grown from say a million solar mass one in  $3 \times 10^9 \text{ yr}$  (i.e. by  $z \sim 2$ ), then we probably need  $L > 0.05 L_{Edd} \sim 10^{45} \text{ erg s}^{-1}$ . This means that the typical growing black hole was powerful and of quasar-like luminosity (indeed housing a quasar at the centre).

Such an obscured powerful object would locally be classified as a ULIRG (see Sanders & Mirabel 1996), although the distant ones need not be the same as the local ones, which are perhaps mainly fuelled by mergers.

Of course it is possible that massive black holes grew inside galaxies which themselves were merging back at  $z \sim 2$ . Nevertheless, unless they were all assembled from smaller holes just before accretion switched off, it is probable that they emit for a reasonable fraction of the last doubling time as a single object.

## 7. OBSCURATION IN A GROWING, ISOTHERMAL GALAXY SPHEROID

Consider an isothermal galaxy in which a significant fraction  $f_c$  of cooled gas remains as cold dusty clouds instead of rapidly forming stars. At the centre a black hole grows by accretion from the surrounding cold (and hot) gas. Assume that the nucleus also blows a wind of velocity  $v_w$  which has a power  $L_w = \alpha L_{Edd}$ . Eventually the wind becomes powerful enough to blow away the surrounding gas and so shut off the accretion and further growth to the black hole and spheroid. The Magorrian et al (1998) black-hole – spheroid mass relation can then be obtained (Silk & Rees 1998; Fabian 1999; Blandford 1999).

The kinetic power of a wind at which it ejects cold gas of column density  $N_H$  from a spheroid is given by

$$L_W \approx 2\pi G M_{sph} m_p N_H v_w$$

or

$$L_w \approx f_c \sigma^4 v_w G^{-1},$$

where  $\sigma$  is the velocity dispersion within the spheroid. (I have used a force argument here, see Fabian 1999; Silk & Rees 1998 use an energy argument to obtain a limit of  $\sigma^5/G$ , which is a factor  $\sigma/v_w$  smaller than the above  $L_w$ .) Ejection occurs when

$$M_{bh} \approx \frac{\sigma^4 \sigma_T}{4\pi G^2 m_p} \frac{v_w}{c} \frac{f_c}{\alpha}.$$

Using the Faber-Jackson relation for spheroids ( $M_{sph} \propto \sigma^4$ ) then yields, if  $\frac{v_w}{c} \frac{f_c}{\alpha} \sim 1$

$$M_b \sim 0.005 M_{sph},$$

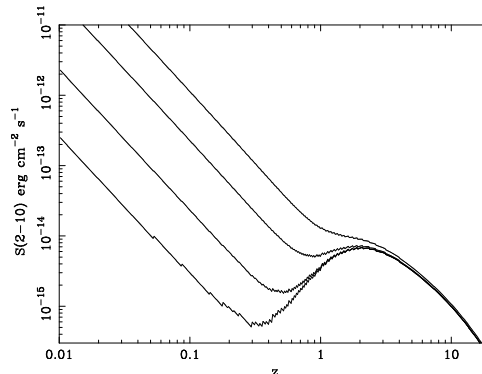


FIGURE 3. The observed 2–10 keV flux as a function of redshift from a source of intrinsic (unabsorbed) 2–10 keV luminosity of  $10^{45}$  erg s $^{-1}$  with a column density of  $10^{24.5}$  cm $^{-2}$ . Scattering fractions (by thin ionized gas) of 5, 1, 0.1 and 0.01 per cent are included (top to bottom). Note that the negative K-correction means that sources at  $z \sim 0.1, 0.8$  and 7 can have the same observed 2–10 keV flux. From Wilman & Fabian (1999).

close to the Magorrian et al (1998) relation.

At that point the column density in to the accretion radius  $N_H \sim N_T = \sigma_T^{-1}$ , so the growth is (just) Compton thick. The growth of massive black holes is radiatively efficient, highly obscured and gives rise to much of the XRB. It is also intimately linked with the growth of galaxy spheroids, the main evolution of which is terminated by a quasar wind. X-ray observations probe best the underlying obscured nucleus at (rest frame) energies of about 30 keV. Indeed X-rays are the best diagnostic of the black hole accretion history of the Universe.

The optically bright quasar phase (from an outside observer's point of view) follows over the next few million years as the accretion disc around the black hole empties. The early phase as the wind clears the gas away can be identified with BAL quasars. The central engine is only revived after the quasar phase if a merger or other event brings in sufficient low angular momentum gas to fuel it.

The prospects of testing the above scenario and absorption models of the XRB are close at hand, with Chandra and XMM. They should detect large numbers of faint, but powerful absorbed sources in the 3–10 keV band, due to the negative K correction involved (see Fig. 3) and identify them with luminous FIR/sub-mm-emitting young galaxy spheroids.

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